CLAIMS

What is claimed is:

1. A method of optimizing a vessel centerline in a digital image, said method comprising the steps of:

providing a digital image of a vessel wherein said image comprises a plurality of intensities corresponding to a domain of points in a D-dimensional space;

initializing a centerline comprising a plurality of points in the vessel;

determining a cross section of the vessel at each point in the centerline;

evaluating a center point for each cross section of the vessel; and

determining a refined centerline from the center points of each cross section.

2. The method of claim 1, wherein the steps of determining a cross section, evaluating a center point, and determining the refined centerline are repeated until the difference between each pair of successive refined centerlines is less than a predetermined quantity.

3. The method of claim 1, wherein the cross section at a point in the centerline is determined by finding a cross section intersecting the centerline with a minimal area.

4. The method of claim 3, wherein the cross section with minimal area is the cross section with the shortest lines intersecting the point in the centerline.

5. The method of claim 1, wherein the cross section at a point on the centerline is perpendicular to a tangent vector of the centerline at the point on the centerline.

6. The method of claim 5, further comprising associating a reference frame to each cross section, wherein each said reference frame is defined by the centerline point in the cross section, and three orthogonal vectors that define an orientation of the reference frame, wherein the three orthogonal vectors include a tangent to the centerline at the centerline point, and two other orthogonal vectors in the plane of the cross section.

7. The method of claim 6, wherein a first referenced frame can be determined from the centerline point in the cross section and the three orthogonal vectors, and a next reference frame can be determined by displacing the first reference frame to a next centerline point and rotating the displaced reference frame to align with the three orthogonal vectors of the cross section associated with the next centerline point.

8. The method of claim 1, wherein evaluating a center point of each cross section comprises finding the contour of the cross section and using the contour to locate the centerpoint of the cross section.

9. The method of claim 1, wherein evaluating a center point of each cross section comprises calculating a centroid of each cross section.

10. The method of claim 9, further comprising calculating the covariance matrix for each cross section, and calculating the eigenvalues and eigenvectors of the covariance matrix to determine the shape of the cross section.

11. The method of claim 6, wherein determining a refined centerline further comprises the steps of:

connecting each successive pair of center points by a virtual spring whose force depends on the difference of the orientations of the pair of center points,

applying a stochastic perturbation to each virtual spring;

determining an optimized cross section of minimal area for each point on the centerline;

finding a center point of the optimized cross section; and

forming a refined centerline by connecting the center points of each optimized cross section.

12. The method of claim 11, wherein the refined centerline is approximated by a least square cubic curve.

13. The method of claim 11, wherein finding a center point of the optimized cross section comprises calculating a centroid of each optimized cross section.

14. The method of claim 11, wherein the spring force connecting two successive centerpoint is defined by $f = k\,(1.0 - T_0 \bullet T_1)$, wherein k is a constant and T_0 and T_1 are the tangent vectors of two successive center points.

15. The method of claim 11, further comprising the step of refining the centerline until it has converged to an optimal centerline, wherein convergence is determined from the displacement of each center point and the deviation of the orientation of each reference plane.

16. The method of claim 15, wherein convergence is determined by considering a maximum of the displacement and orientation as defined by

$$\left(DS^k_{\max}, DV^k_{\max}\right) = \max_{i=1}^{n}\left(\left|C_i^k - P_i^k\right|, 1 - T_i^k \bullet N_i^k\right),$$

where $DS^k_{\max}$ is the maximum displacement and $DV^k_{\max}$ is the maximum deviation of tangent vector at the k^{th} iteration, C_i^k is the i^{th} updated center point, P_i^k is the position of the i^{th} reference frame, T_i^k is the i^{th} updated tangent direction and N_i^k is the normal of the i^{th} reference frame at the k^{th} iteration.

17. The method of claim 15, wherein convergence is determined by considering an average of the displacement and orientation as defined by

$$\left(DS^k_{avg}, DV^k_{avg}\right) = \frac{1}{N}\sum_{i=1}^{n}\left(\left|C_i^k - P_i^k\right|, 1 - T_i^k \bullet N_i^k\right)$$

where DS^k_{avg} is the average displacement and DV^k_{avg} is the average deviation of tangent vector at the k^{th} iteration, C_i^k is the i^{th} updated center point, P_i^k is the position of the i^{th} reference frame, T_i^k is the i^{th} updated tangent direction and N_i^k is the normal of the i^{th} reference frame at the k^{th} iteration.

18. The method of claim 5, further including calculating the lumen and wall contours on each cross-section, as well as other geometric information about these two contours.

19. The method of claim 1, further comprising the step of providing an endoluminal flight along the centerline of a vessel object, displaying hard plaque and soft plaque in different colors for differentiation from the vessel wall.

20. The method of claim 19, further comprising moving back and forth along the centerline by direct manipulation of a mechanism.

21. The method of claim 20, wherein the mechanism includes clicking or dragging a mouse along an overview of the entire vessel or scrolling a mouse wheel to scroll along the centerline of the vessel.

22. The method of claim 20, wherein the mechanism includes interactively tilting a viewpoint without leaving the centerline of the vessel.

23. A method of optimizing a vessel centerline in a digital image, said method comprising the steps of:

providing a digital image of a vessel wherein said image comprises a plurality of intensities corresponding to a domain of points in a D-dimensional space;

initializing a centerline comprising a plurality of points in the vessel;

determining a cross section of the vessel at each point in the centerline, wherein the cross section at a point on the centerline is perpendicular to a tangent vector of the centerline at the point on the centerline;

associating a reference frame to each cross section, wherein each said reference frame is defined by the centerline point in the cross section, and three orthogonal vectors that define an orientation of the reference frame, wherein the three orthogonal vectors include a tangent to the centerline at the centerline point, and two other orthogonal vectors in the plane of the cross section;

evaluating a center point for each cross section of the vessel by calculating a centroid of each cross section;

connecting each successive pair of center points by a virtual spring whose force is defined by $f = k\,(1.0 - T_0 \bullet T_1)$, wherein k is a constant and T_0 and T_1 are the tangent vectors of two successive center points;

applying a stochastic perturbation to each virtual spring;

determining an optimized cross section of minimal area for each point on the centerline;

finding a center point of the optimized cross section by calculating its centroid;

forming a refined centerline by connecting the center points of each optimized cross section; and

refining the centerline until it has converged to an optimal centerline, wherein convergence is determined from the displacement of each center point and the deviation of the orientation of each reference plane.

24. The method of claim 23, wherein a first referenced frame can be determined from the centerline point in the cross section and the three orthogonal vectors, and a next reference frame can be determined by displacing the first reference frame to a next centerline point and rotating the displaced reference frame to align with the three orthogonal vectors of the cross section associated with the next centerline point.

25. The method of claim 23, further comprising calculating the covariance matrix for each cross section, and calculating the eigenvalues and eigenvectors of the covariance matrix to determine the shape of the cross section.

26. The method of claim 23, wherein the refined centerline is approximated by a least square cubic curve.

27. The method of claim 23, wherein convergence is determined by considering a maximum of the displacement and orientation as defined by

$$\left(DS^k_{\max}, DV^k_{\max}\right) = \max_{i=1}^{n}\left(\left|C_i^k - P_i^k\right|, 1 - T_i^k \bullet N_i^k\right),$$

where $DS^k_{\max}$ is the maximum displacement and $DV^k_{\max}$ is the maximum deviation of tangent vector at the k^{th} iteration, C_i^k is the i^{th} updated center point, P_i^k is the position of the i^{th}

reference frame, T_i^k is the i^{th} updated tangent direction and N_i^k is the normal of the i^{th} reference frame at the k^{th} iteration.

28. The method of claim 23, wherein convergence is determined by considering an average of the displacement and orientation as defined by

$$\left(DS_{avg}^k, DV_{avg}^k\right) = \frac{1}{N}\sum_{i=1}^{n}\left(\left|C_i^k - P_i^k\right|, 1 - T_i^k \bullet N_i^k\right)$$

where DS_{avg}^k is the average displacement and DV_{avg}^k is the average deviation of tangent vector at the k^{th} iteration, C_i^k is the i^{th} updated center point, P_i^k is the position of the i^{th} reference frame, T_i^k is the i^{th} updated tangent direction and N_i^k is the normal of the i^{th} reference frame at the k^{th} iteration.

29. The method of claim 23, further including calculating the lumen and wall contours on each cross-section, as well as other geometric information about these two contours.

30. The method of claim 23, further comprising the step of providing an endoluminal flight along the centerline of a vessel object, displaying hard plaque and soft plaque in different colors for differentiation from the vessel wall.

31. The method of claim 30, further comprising moving back and forth along the centerline by direct manipulation of a mechanism.

32. The method of claim 31, wherein the mechanism includes clicking or dragging a mouse along an overview of the entire vessel or scrolling a mouse wheel to scroll along the centerline of the vessel.

33. The method of claim 31, wherein the mechanism includes interactively tilting a viewpoint without leaving the centerline of the vessel.

34. A program storage device readable by a computer, tangibly embodying a program of instructions executable by the computer to perform the method steps for optimizing a vessel centerline in a digital image, said method comprising the steps of:

providing a digital image of a vessel wherein said image comprises a plurality of intensities corresponding to a domain of points in a D-dimensional space;

initializing a centerline comprising a plurality of points in the vessel;

determining a cross section of the vessel at each point in the centerline;

evaluating a center point for each cross section of the vessel; and

determining a refined centerline from the center points of each cross section.

35. The computer readable program storage device of claim 34, wherein the method steps of determining a cross section, evaluating a center point, and determining the refined centerline are repeated until the difference between each pair of successive refined centerlines is less than a predetermined quantity.

36. The computer readable program storage device of claim 34, wherein the cross section at a point in the centerline is determined by finding a cross section intersecting the centerline with a minimal area.

37. The computer readable program storage device of claim 36, wherein the cross section with minimal area is the cross section with the shortest lines intersecting the point in the centerline.

38. The computer readable program storage device of claim 34, wherein the cross section at a point on the centerline is perpendicular to a tangent vector of the centerline at the point on the centerline.

39. The computer readable program storage device of claim 38, the method further comprising the step of associating a reference frame to each cross section, wherein each said reference frame is defined by the centerline point in the cross section, and three orthogonal vectors that define an orientation of the reference frame, wherein the three orthogonal vectors include a tangent to the centerline at the centerline point, and two other orthogonal vectors in the plane of the cross section.

40. The computer readable program storage device of claim 39, wherein a first referenced frame can be determined from the centerline point in the cross section and the three orthogonal vectors, and a next reference frame can be determined by displacing the first reference frame to a next centerline point and rotating the displaced reference frame to align with the three orthogonal vectors of the cross section associated with the next centerline point.

41. The computer readable program storage device of claim 34, wherein evaluating a center point of each cross section comprises finding the contour of the cross section and using the contour to locate the centerpoint of the cross section.

42. The computer readable program storage device of claim 34, wherein evaluating a center point of each cross section comprises calculating a centroid of each cross section.

43. The computer readable program storage device of claim 42, wherein the method further comprises calculating the covariance matrix for each cross section, and calculating the eigenvalues and eigenvectors of the covariance matrix to determine the shape of the cross section.

44. The computer readable program storage device of claim 39, wherein determining a refined centerline further comprises the steps of:

connecting each successive pair of center points by a virtual spring whose force depends on the difference of the orientations of the pair of center points,

applying a stochastic perturbation to each virtual spring;

determining an optimized cross section of minimal area for each point on the centerline;

finding a center point of the optimized cross section; and

forming a refined centerline by connecting the center points of each optimized cross section.

45. The computer readable program storage device of claim 44, wherein the refined centerline is approximated by a least square cubic curve.

46. The computer readable program storage device of claim 44, wherein finding a center point of the optimized cross section comprises calculating a centroid of each optimized cross section.

47. The computer readable program storage device of claim 44, wherein the spring force connecting two successive centerpoint is defined by $f = k\,(1.0 - T_0 \bullet T_1)$, wherein k is a constant and T_0 and T_1 are the tangent vectors of two successive center points.

48. The computer readable program storage device of claim 44, wherein the method further comprises the step of refining the centerline until it has converged to an optimal centerline, wherein convergence is determined from the displacement of each center point and the deviation of the orientation of each reference plane.

49. The computer readable program storage device of claim 48, wherein convergence is determined by considering a maximum of the displacement and orientation as defined by

$$\left(DS_{\max}^{k}, DV_{\max}^{k}\right) = \max_{i=1}^{n}\left(\left|C_i^k - P_i^k\right|, 1 - T_i^k \bullet N_i^k\right),$$

where $DS_{\max}^{k}$ is the maximum displacement and $DV_{\max}^{k}$ is the maximum deviation of tangent vector at the k^{th} iteration, C_i^k is the i^{th} updated center point, P_i^k is the position of the i^{th} reference frame, T_i^k is the i^{th} updated tangent direction and N_i^k is the normal of the i^{th} reference frame at the k^{th} iteration.

50. The computer readable program storage device of claim 48, wherein convergence is determined by considering an average of the displacement and orientation as defined by

$$\left(DS_{avg}^{k}, DV_{avg}^{k}\right) = \frac{1}{N}\sum_{i=1}^{n}\left(\left|C_i^k - P_i^k\right|, 1 - T_i^k \bullet N_i^k\right)$$

where DS_{avg}^{k} is the average displacement and DV_{avg}^{k} is the average deviation of tangent vector at the k^{th} iteration, C_i^k is the i^{th} updated center point, P_i^k is the position of the i^{th} reference frame, T_i^k is the i^{th} updated tangent direction and N_i^k is the normal of the i^{th} reference frame at the k^{th} iteration.

51. The computer readable program storage device of claim 38, wherein the method further includes calculating the lumen and wall contours on each cross-section, as well as other geometric information about these two contours.

52. The computer readable program storage device of claim 34, wherein the method further comprises the step of providing an endoluminal flight along the centerline of a vessel object, displaying hard plaque and soft plaque in different colors for differentiation from the vessel wall.

53. The computer readable program storage device of claim 52, wherein the method further comprising moving back and forth along the centerline by direct manipulation of a mechanism.

54. The computer readable program storage device of claim 53, wherein the mechanism includes clicking or dragging a mouse along an overview of the entire vessel or scrolling a mouse wheel to scroll along the centerline of the vessel.

55. The computer readable program storage device of claim 53, wherein the mechanism includes interactively tilting a viewpoint without leaving the centerline of the vessel.